Large Floating Concrete LNG/LPG Offshore Platforms

By Dale Berner, Ph.D. and Ben C. Gerwick

A number of studies and projects for large floating concrete offshore platforms with storage capacity for liquefied natural gas, LNG, and liquefied petroleum gas, LPG, have demonstrated the feasibility and significant advantages of such structures. These platforms, which tend to be large in order to take advantage of economies of scale, can be used for production, storage, off-loading, and re-gasification. With the recent increase in the price of gas, the general consensus in the industry is that several such platforms (using either steel or concrete hulls) will be built within the next ten years.

Cryogenic liquids such as LPG and LNG, are typically stored at temperatures ranging from approximately –40 ºC, to –160 ºC, respectively, and are highly flammable. Prestressed concrete hulls have several advantages over steel hulls for containing such cryogenic liquids including: excellent resistance to cryogenic temperatures and thermal shock, and excellent marine performance. Indeed, one such floating concrete structure that Ben C. Gerwick, Inc. has worked on, the Ardjuna Sakti LPG terminal, has been in service since 1975, with good service performance.

This paper discusses several key aspects of such platforms including:

1) *Material selection and performance, including the use of lightweight concrete and cryogenic steels.*
2) *Thermal stress and strain considerations, including both global and local concerns.*
3) *Platform construction consideration, including construction in areas with shallow water.*

INTRODUCTION

Liquefied Natural Gas, LNG, at approximately –160ºC, and Liquefied Petroleum Gas, LPG, at approximately –40ºC, occupy approximately 630 times, and 310 times, less volume than their respective gas forms at stand temperature and pressure. This volume reduction allows these cryogenic products to be transported overseas. Floating offshore LNG/LPG storage platforms can serve at either end of the transport route, either as a liquefaction, or as a re-gasification, facility. Such floating facilities offer several advantages over conventional land-based facilities for offshore fields, such as: a) the elimination of both harbor facilities and of long pipelines from the production platform to shore; b) the ability to relocate the facilities from one field to another (which encourages more rapid depletion of small fields); c) faster field development time, particularly for remote fields, with little or no site development work; d) normal processing procedures such as separation and dehydration can be performed along with the LNG/LPG manufacturing; e) better control of construction schedules and costs; f) the plant can be commissioned in transit to the operation site, thus reducing the time to start-up; and e) enhanced safety by isolating the facilities away from populated areas.

Ben C. Gerwick, Inc. has been involved with floating LNG/LPG offshore platforms ever since before the Ardjuna Sakti LPG floating concrete terminal (60,000 DWT, see Figure 1) was install in Indonesia, for ARCO, in 1975.

While the Ardjuna Sakti has proven the viability of such cryogenic storage platform technology for LPG, only relatively recently have advances in technology and changes in market conditions made a similarly compelling case for the development of floating LNG platforms. Currently, this case has only been made convincingly for relatively benign environments such as West Africa, Southeast Asia, and the Caribbean.

Fig. 1. Ardjuna Sakti LPG Floating Concrete Terminal

Numerous cryogenic storage platforms will soon be required to: a) develop stranded offshore gas fields identified over the past several decades but which are too small to develop conventionally; b) improve the economics of associated gas which can no longer be flared, and which is an expense re-inject; and c) to expedite, and improve the economics of large offshore gas fields. Still further platforms will be required to serve as floating re-gasification facilities near populated markets. To further improve their economics, and also to improve their technical viability, proposed LPG/LNG liquefaction platforms tend to be large; which allows the platform to support large topside processing facilities, and which typically results in improved wave response. Topside liquefaction processing facilities are sensitive to wave induce motions; however, recent processing advancement allow processing to continue over a wider range of motion.

Currently, ship-shaped FPSO's, are the most commonly proposed platform configuration. Such platforms provide the combined benefits of: a) a large topside area; b) a large storage volume; c) the ability to weathervane into on-coming waves; d) the feasibility of conventional offloading schemes in benign areas, and e) good economics. However, this configuration is not suitable for deepwater developments, and has undesirable motions in harsh wave climates. For harsher wave climates, alternate configurations have been proposed including: torus-shapes (See Figure 2), spar platforms, and semi-submersible vessels. Another variation of platform configuration, which is not discussed in this paper, is the float-in Gravity Base Structure, GBS, which has been seriously proposed for several locations around the world, and which are typically designed using concrete hulls.

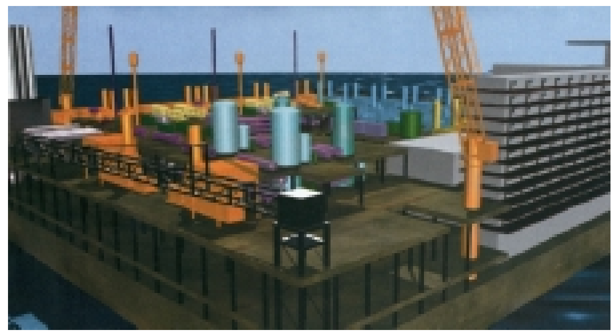

Fig. 2. Torus-Shaped Floating Concrete LNG Terminal

STEEL HULLS VS. CONCRETE HULLS

Prestressed concrete has been used in the onshore storage of liquefied gases since the 1950's; however, relatively few concrete containment structures were constructed prior to the 1970's. Since the 1970's, the proportion of onshore concrete containment tanks has been gaining rapidly, compared to steel containment tanks, largely due to prestressed concrete's excellent service record.

The use of steel hulls for floating platforms has also generally been more common offshore than the use of concrete hulls. However, concrete hulls have performed well offshore, and they offer a unique combination of advantages over steel hulls for cryogenic containment; which should make them more common for floating LNG/LPG applications than is generally the case offshore. Table 1 provides a comparison of advantages for both concrete, and steel, hulls for LNG storage.

Table 1: Comparison of Advantages Between Concrete and Steel Hulls for LNG Storage

ADVANTAGES FOR CONCRETE HULLS	ADVANTAGES FOR STEEL HULLS
Superior Cryogenic Behavior	Fabrication in Existing Shipyards
Good Separation of Processing/Storage	Potentially Lower First Cost for One Hull
Reduced Down-Time due to Inspection	Traditional Engineering
Reduced Maintenance Costs	Traditional Construction
Economies of Scale	More Steel Fabricators are Available
Good Impact Resistance	More Steel Designers are Available
Low Center of Gravity/Good Station Keeping Behavior/Reduced Motions	Greater Flexibility Reduces Thermal Stresses
Excellent Fatigue Life	Not Subject to Freeze-Thaw Damage
High Mass Moment of Inertia	Prestressing Not Required
Slower Thermal Response/Better Insulation	Impermeable to Gas and Liquids
Resistance to Fatigue and Crack Propagation	Similar to Numerous LNG/LPG Ships
Resistance to Buckling	Does not Require a Membrane Liner

Properties of Prestressing and Mild Reinforcing Steel at Low Temperatures

As a composite material, the behavior of reinforced/prestressed concrete is influenced as much by the mild reinforcing, and high-strength prestressing, steel as by the concrete. At low temperatures, such steels typically gain from 4 to 30 percent in yield and/or ultimate tensile strength, while they typically become somewhat less ductile, depending on the steel composition. For proper design against stress concentrations, rapid loadings, and fatigue, as well as for favorable post-ultimate behavior at both ambient and low temperatures, the reinforcing steel must exhibit a combination of both strength and ductility, jointly termed toughness. Toughness is a property measured independently of an element's configuration and is a measure of the amount of energy that the material can absorb before failure.

Reinforcing steels can broadly be divided into ferritic steels, with a body-centered cubic crystal lattice structure, and austenitic steels with a face-centered cubic lattice structure. Ferritic steels tend to be less expensive but more brittle, and less tough, than austenitic steels. Toughness can be promoted by controlling the steel processing to induce a fine-grained lattice structure containing austensite; however, depending on the design requirements it may be more economical to select a ferritic steel with a fine grain structure with a minimum number of lattice defects. Processes that promote tough, ductile steels, include deoxidizing with silicon, or aluminum, heat treating, and cold-working.

High-strength, prestressing, steels that retain a good degree of toughness at low temperatures can be divided into three groups: a) carbon-manganese cold-drawn wire and strands; b) high-tensile strength steel alloy bars, and c) stainless steels.

Cold-drawn wires and strands are most commonly used for prestressing at both ambient and low temperatures due to their combination of relatively low cost, high strength and good ductility. The usual process for manufacturing prestressing wire and strands entails a controlled cooling procedure from the austenite temperature range to give the ferritic steel a desirable microstructure for cold-drawing. The cold working improves the strength and cryogenic properties of the steel, but cold-working also induces undesirable stresses that are typically removed by further heat treatment. These cold-drawn steels are not weldable due to their high carbon contents.

Both the steel alloy bars and stainless steels are more costly than cold-drawn wires and strands; but their typically greater ductility may make them appropriate for selected applications. High-tensile strength alloy steels include silicon chromium wires and bars, 9-percent nickel steel bars, and micro-alloyed bars. These alloy steels may contain combinations of ferritic and austenitic matrix structures. High-strength stainless steels contain large quantities of chromium (15 to 20%), and nickel (8 to 10 percent); which induce an austenitic lattice structure. These stainless steels have excellent cryogenic properties, they are highly corrosion resistant, and are readily welded; however, they are also relatively expensive.

Common grades of mild reinforcing steel, with from 0.1 to 0.2 percent carbon, generally retain sufficient toughness above 0ºF (-18ºC) to be used where lower temperatures are not expected. Below this temperature, higher quality control standards need to be established for the steel with regard to chemical composition, heat treatment, and cold working. Due consideration also needs to be made for the potential dynamic loading and for the desired level of safety.

Cryogenic grades of passive reinforcement can be provided by replacing the mild reinforcing steel with passive prestressing steel; however, this can add unnecessary expense, and may not fully satisfy ductility requirements, strain capacity requirements, or steel/concrete bond requirements. Consequently, some special grades of deformed rebars have been developed for cryogenic use by maintaining high quality control in processing.

Cryogenic grades of mild reinforcing steels can be roughly divided into three groups: a) carbon-manganese steels; b) austenitic steels; and c) austenitic-ferritic steels. Carbon-manganese steels, are the most cost-effective of these three groups, and have a fine-grained ferritic matrix structure, frequently modified by the additions of such elements as niobium, and molybdenum. The austenitic steels may have limited applications due to their high cost and typically have lower yield and ultimate tensile strengths than the carbon-manganese steels. The austenitic-ferritic steels incorporate nickel to produce a fine nickel-rich ferrite grain structure bounded by small quantities of reformed austenite to provide ductility.

Prestressed Concrete Material Performance

Due to conservative design and the inherent capacity of load-carrying membrane structures, failures related purely to design have been rare. Several recent failures; however, have indicated that deficiencies in materials and/or construction methods, especially when combined with factors such a thermal stress, fatigue degradation, creep, and freeze-thaw damage, can be important.

<u>Selected desirable material behavior of prestressed concrete for hulls</u>:

1. At low temperatures, the strength of concrete increases, while neither the prestressing steel nor the reinforced concrete become brittle at low temperatures.

2. When loaded to failure, prestressed concrete is not subject to sudden progressive collapse. Also, cracks from temporary overload tend to close upon removal of the overload.

3. Proper prestressing will keep the concrete watertight and free from any major through cracking. Additionally, concrete, that is continually moist, will continue to hydrate, which can "heal" any minor static cracks that have occurred. Furthermore, moist lightweight concrete has extremely low permeability at cryogenic temperatures.

<u>Selected undesirable material behavior of prestressed concrete for hulls:</u>

1. If moisture in the form of water vapor is present, it will permeate the concrete and migrate to the cold face, where it will freeze, thus tending to debond the membrane (thus the nitrogen gas, that is typically circulated between the hull and the primary containment tanks, should be dessicated to prevent this).

2. Global thermal shortening in un-insulated tank walls can potentially produce through-thickness cracks unless offset by prestressing (which can readily be provided).

3. If no membrane is used, the cryogenic liquid will permeate the outer layer of concrete over time. If the tank is then taken out of service and warms up rapidly, gas will be generated that may cause local spalling (therefore membrane liners are required).

Most concrete offshore structures have been built with standard weight concrete, including the Ardjuna Sakti and the N'KOSSA floating terminals. However, the more sophisticated concrete platforms including Troll, Hibernia, and Draugen have used modified density concrete, and some of the most relevant platforms including Super CIDS, Tarsiut, and Heidrun have used high-strength lightweight concrete. Therefore, a brief discussion of the key differences in these materials is provided.

Standard weight concrete is more widely available, is less expensive, and generally has both higher compressive, and higher shear, strength than either modified density, or lightweight, concrete. However, as cited above, although most offshore platforms/terminals use standard weight concrete, the more sophisticated, and more relevant, platforms have used either specified density, or lightweight, concrete for reasons including: 1) reduced deformation (thermal, shrinkage, etc.) loads; 2) reduced draft, and 3) better durability. By using modified density concrete little, or no, reduction in design compressive strength or design shear strength need to be taken into account, while lightweight concrete normally requires a reduction in both of these design values. However, the use of lightweight concrete has several advantages at cryogenic temperatures as compared to standard weight concrete including:

Plain lightweight concrete has approximately twice the tensile strain at cracking as plain standard weight concrete, and thus can sustain twice the thermal deformations before cracking. Furthermore, the modulus of elasticity of lightweight concrete can be about half that of standard weight concrete, thus prestressing of the lightweight concrete will result in proportionately greater resistance to thermally induced cracking than standard weight concrete.

Air entrained lightweight concrete has been 200 and 1,000 times lower permeability than standard weight concrete, at both room and cryogenic temperatures. This raises the possibility of eliminating the vapor barrier if high strength air entrained lightweight concrete is used.

The coefficient of thermal expansion/contraction of lightweight concrete is approximately $7 \times 10^{-6}/^{o}C$ as compared to $10 \times 10^{-6}/^{o}C$ for standard weight concrete. This results in lower thermal deformations and lower thermally induced stresses/strains for lightweight concrete.

The coefficient of thermal conductivity is approximately 30% lower for high strength lightweight concrete as compared to standard weight concrete. This would result in lower boil-off of LNG/LPG for a lightweight concrete hull.

Thermal Strains/Stresses

Thermal contraction and expansion of members of an LNG/LPG storage vessel, during both scheduled, and accidental, cooling and warming cycles, induce thermal stresses that depend on: a) internal restraint for members subject to thermal gradients, b) external restraint of members subject to an absolute temperature change, and c) differential restraint for members containing materials with different coefficients of thermal expansion/contraction. For simple cases, restraint factors can be used together with the coefficients of thermal expansion/contraction and the temperature change in order to calculate the induced thermal stresses. For more complicated cases, finite element analysis are required (see Figure 3).

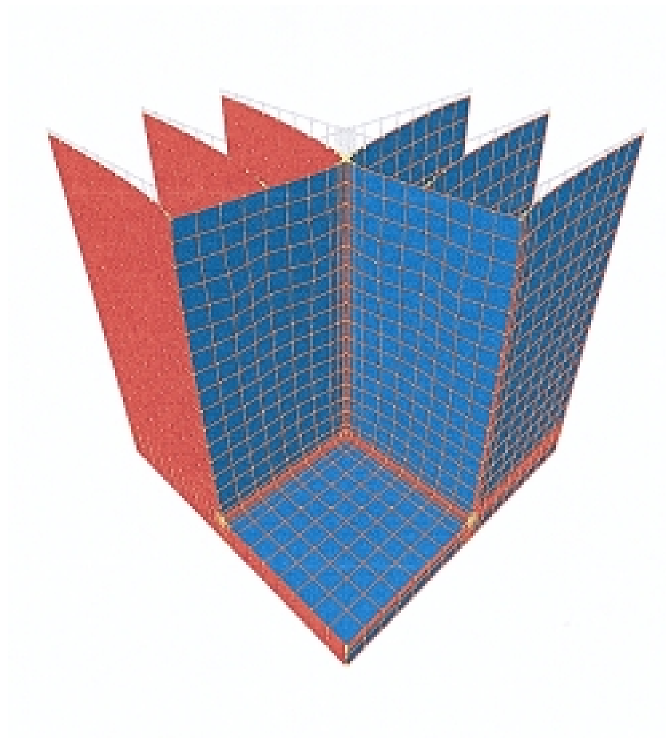

Figure 3. F.E.M. Model for Thermal Analysis of Floating Concrete LNG Terminal

Determination of thermal strains requires an understanding of the coefficient of thermal contraction/expansion for the composite member section; however, this composite behavior is dominated by the concrete response, which in turn is primarily influenced by the contraction/expansion of the aggregate. Use of aggregates such as expanded shale not minimizes thermal expansion and contractions, but they also reduce the induced thermal stresses by reducing the stiffness of the structure, thus allowing it to comply with the expansions/contractions, which occur.

Virtually all offshore LNG containment vessel designs utilize a primary containment system that insulates the concrete hull from the cryogenic liquid, because the global thermal stresses induced in the hull during cooling and warming cycles would be excessive. However, the appropriate use of prestressing, doublehull configuration, and material selection can allow LPG floating containment vessel to use the inner hull as a primary containment system subjected to cryogenic temperatures on a regular basis, because the local and global thermal stresses are more manageable. Indeed, concrete offshore platforms deployed in the Arctic regularly sustain temperatures colder than those associated with containing LPG, and have performed extremely well for decades (see Figure 4). This consideration can result in significant savings in containment costs for a concrete LPG vessel as compared to a steel LPG vessel.

Figure 4. Arctic Platform at Cryogenic Temperatures

CONSTRUCTION CONSIDERATIONS

Not only to concrete floating platforms typical have deeper drafts than comparable steel floating platforms, but also concrete platforms typically demonstrate improving economics with increasing size, relative to steel platforms. Thus construction considerations for such large-floating concrete LNG/LPG offshore platforms merit careful evaluation due to the size and draft relative to existing conventional facilities.

Small barge shaped concrete floating platforms such as the Ardjuna Sakti LPG terminal, of the N'KOSSA oil terminal, can be built in large conventional shipyards, or existing graving docks. Similarly, square torus-shaped floating platforms such as that shown in Figure 2 have been designed to be formed by joining afloat four smaller barge shaped concrete vessels that were planned to be fabricated in large conventional shipyards.

Deeper draft concrete semi-submersible platforms, such as the Troll Oil platform in the North Sea, can either be built by beginning construction in a graving dock, and then float-out to deeper water for completion afloat, or if deeper water is not available near shore, they can be designed to be completed while floating on their pontoons.

Still deeper draft concrete floating platforms such as spars and semi-spars can either be built in a manner similar to a conventional concrete Condeep GBS if protected deep water is available for slip-forming the concrete shaft(s) while floating in the protected deep water (see Figure 5), or if such protected deep water is not available then single shaft concrete spars can be constructed horizontally and then floated out to deep water for up-ending in a manner similar to steel spar platforms.

Figure 5. Slip-Forming a Condeep Platform

RECOMMENDATIONS

In addition to the storage plans considered in this paper, it is recommended that investigations be made to determine the feasibility of storing and transporting pressurized LNG, using floating prestressed concrete structures. As noted previously, LNG at atmospheric pressure is stable at approximately –162 ºC (-260 ºF), while LNG stored at the pressure at 170 m (560 ft) water depth is stable at approximately –109 ºC (-164 ºF). This could significantly reduce the CAPEX, and OPEX of the liquefaction facilities. Furthermore, demands on the membrane liners, and the time of cool-down/warm-up, would be reduced.

Figures 6 and 7 show a conceptual prestressed concrete storage/transport vessel suitable for containing pressurized LNG. Prestressed concrete is economical to use for the construction of such a large pressure vessel, costing less than half that for steel construction.

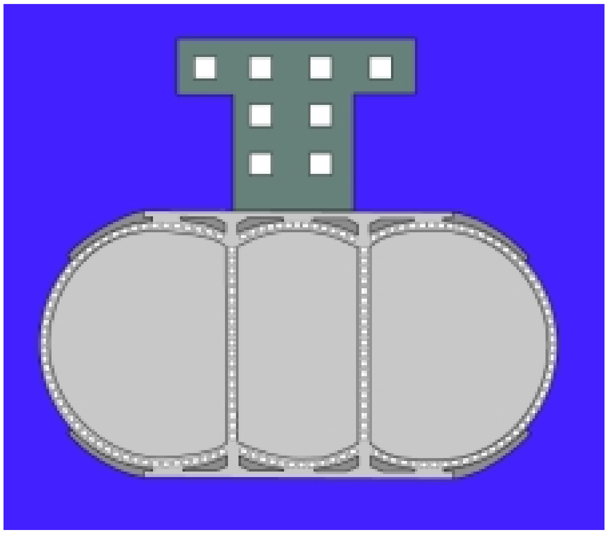

Figure 6. Cross-Section of Conceptual Pressurized LNG Storage/Transport Vessel

ACKNOWLEDGMENTS

Some of the information presented in this paper is based on the findings of a study conducted for Mobil Technology Company, to determine the structural feasibility of storing LNG in concrete structures afloat in the open ocean.

REFERENCES

1. Berner, D. E., Gerwick, B. C., and Polivka, M., "Static and Cyclic Behavior of Structural Lightweight Concrete at Cryogenic Temperatures," ASTM, Special Technical Testing Publication 858, 1985.

2. Berner, D. E., Behavior of Prestressed Concrete Subjected to Low Temperatures and Cyclic Loading, Dissertation, U. C. Berkeley, 1984.

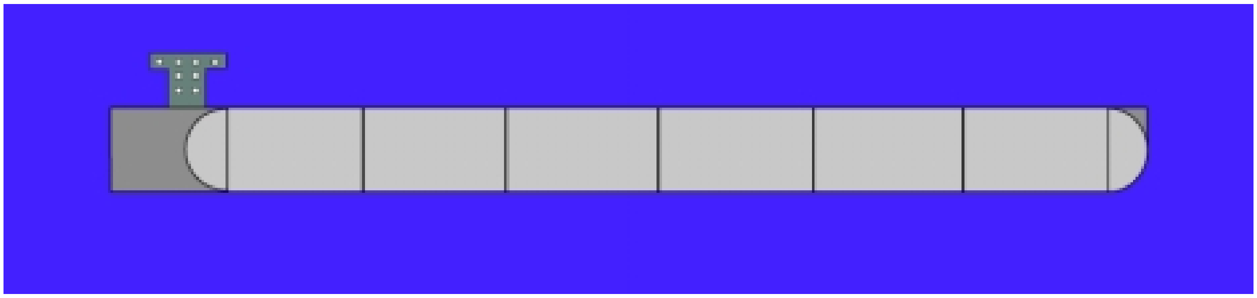

Figure 7. Longitudinal Cross-Section of Pressurized LNG Storage/Transport Vessel